Hadronic Dark Matter Searches at CMS at $\sqrt{s} = 13$ TeV

Searches for semi-visible jets and invisibly decaying Higgs bosons

By

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Word count: number in words

Abstract

Here goes the abstract

Dedication and acknowledgements

This work is dedicated to my grandfather, Dato' Mahindar Singh Bhal, who was able to begin this journey with me but sadly unable to finish it.

There are far too many people and too little space to individually thank everyone who has accompanied me during this PhD, but I'll try my best.

Firstly, to my supervisor, Dr. Henning Flächer. Your advice and guidance over the course of this degree has been instrumental to achieving it, as well as encouraging my growth as a researcher.

Secondly, to all my colleagues at the University of Bristol. Very little would have been achieved without your help. From scientific discussions in the pub to pub discussions in the physics building, they have all been fruitful either directly or by helping me detach from work. Special thanks are in order to Simone and Sam Maddrell-Mander in my cohort, who have put up with my complaining during the stressful times.

To my friends from Monmouth that include my best friends in the world, Mike, James, Sneddon, (Mini) Sam, and Matt Bristow. You've been on this adventure with me since our school days and had my back the entire time. We've been through the highest, lowest, and most hilarious times together. I can definitively say I would not be the person I am today without you.

To my friends from LTA and those based at CERN, especially Matt Heath, Dwayne and Vukasin. You became my second family while I was in Geneva. I'll miss the skiing, trips into the city, games, and general banter.

To my undergraduate cohort from Exeter. Though our meet ups are rare, I always look forward to our group holidays and hope they continue far into the future.

Lorenza Iacobuzio, you get a special mention. While we weren't especially close until recently, you've been my sage, partner in food, and exceptional friend when I've needed it the most.

Finally, and most importantly, my family deserve my thanks. You have been there for me since the very beginning supporting me through school, undergrad, PhD, and every other endeavour. To my grandparents, uncles, aunties, and cousins, my siblings Joe, Lydia, Sitara, and Arjen, my stepmum Nadia, and my cat Pixie, I am sincerely grateful to have you in my lives. But above all else, to my mum Meeta and dad Kiron, I could not have done any of this without you and as such, you have my deepest and most heartfelt love and gratitude.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

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CHAPTER 1

INTRODUCTION

The universe, in all its vastness, structure, natural laws and chaos, is comprised of only three principal components: visible matter, the ingredients of stars, planets and life, is the only one we interact with on a regular basis; dark energy, a force or manifestation of something even more mysterious, responsible for the accelerating expansion of the universe, is almost entirely unknown; and dark matter, a substance invisible in all sense of the word, that binds galaxy together and influences large scale structure in the cosmos, is the focus of this thesis.

1.1 Evidence for dark matter

The observable universe contains a major component that is not explained by conventional standard model (SM) physics. Making up approximately 25.8% of the energy density of the universe [44], the astrophysical evidence suggests that there exists a massive, neutral constituent that has a significant gravitational influence on the visible matter we observe. Labelled “dark matter", this entity has captured the interest of many scientists. Those in particle physics have developed theories and experimental searches in an attempt to understand the characteristics of dark matter.

Dark matter was thought to be created in the hot, early universe when the thermal background allowed its spontaneous pair production. When the universe expanded and cooled, a thermal freeze out occurred: the average temperature became too low to allow significant production [7]. Matter became further separated and the dark matter annihilation rate decreased, leaving a “thermal relic". These remaining particles were attracted via gravity, the only known force by which dark matter interacts. They formed filaments throughout the universe, and the potential wells they induced allowed the progenitors of galaxies to form within.

Although dark matter cannot be directly studied with conventional astronomy, there are several independent astrophysical observations that suggest its existence. The rotation curves of most galaxies are roughly flat [42], contrary to the expected Keplerian curve ($v \propto 1/\sqrt{r}$) from solely baryonic matter. On the galactic scale, dark matter is sprinkled in a roughly spherical halo that spans beyond the observable disc. The inclusive dark matter mass increases linearly [22] to compensate for the decline expressed by visible matter [9, 24]. Weak gravitational lensing of galaxies can cause images to appear distorted from dark matter between the galaxy and observer warping its local spacetime [30].

From these observations, several properties of dark matter can be inferred. It is electrically neutral as it does not interact with light. It is “cold" (non-relativistic), implying its rest mass energy is much greater than the thermal background in the universe. Current estimates suggest its mass is at the gigaelectron volt (GeV) or teraelectron volt (TeV) scale [29, 34, 38]. If it were on the neutrino scale – and therefore relativistic – it would be too diffuse to condense and allow galaxy formation. This supports the idea of “bottom-up” structure formation in the universe; smaller galaxies form around dark matter clumps, then merge to form larger structures [49]. This also asserts that dark matter is stable, at least on the timescale of the age of the universe.

1.1.1 Overview of dark matter searches

Whilst all current evidence has been astrophysical, determining the properties of dark matter falls into the realm of particle physics. Of the three types of dark matter searches, its production from high-energy collisions is being probed at the LHC. Protons are collided at energies sufficient to produce the heavy particles that existed in the high-temperature early universe. The Compact Muon Solenoid (CMS) experiment utilises its general purpose detector to allow physicists to search for dark matter in different theoretical frameworks.

Despite the standard model providing precise predictions of three of the four fundamental forces and the particles that they interact with, it does not substantiate the existence of dark matter. Several theories that are beyond (BSM), or extend, the standard model can accommodate dark matter candidates such as sterile neutrinos [21], axions [20], and Kaluza-Klein states [27].

I have so far searched for dark matter in the context of supersymmetry (SUSY) [35]. The theory introduces a spin symmetry that predicts a fermionic superpartner for each boson, and vice versa. If the lightest supersymmetric particle (LSP) is stable and electrically neutral, it would provide a promising dark matter candidate. Expected SUSY particle decays produce the LSP and, typically, hadronic jets because of the initial state particles. As lightest supersymmetric particles (LSPs) are undetectable, a reconstructed event from a detector would show a momentum imbalance. It contains "missing" transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) which is required to satisfy energy and momentum conservation. So the characteristics of SUSY in a collider would be high $E_{\mathrm{T}}^{\mathrm{miss}}$ from the LSPs, and several jets. But as no hint of supersymmetry has been found, other theories and simplified models from more complete theories have been considered. These are discussed later on.

There is significant motivation to study dark matter from a wider, as well as a more personal, viewpoint. It is important to understand how the universe operates, and dark matter opens up the potential for new physics that improves our understanding of nature. My personal interests include the blend of particle physics and astrophysics, and the opportunity to discover and add to humanity's collective wisdom. With a projected 130 fb^{-1} from the LHC Run-2 at a centre-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$, there is great potential to constrain some of the properties of dark matter.

- Thought to be made of a neutral, weakly interacting particle. Because it's neutral (and thought to be elementary), it cannot couple to the electromagnetic field, so there's no way to detect it through conventional astronomy.
- Galaxies form and condense in dark matter wells because the baryonic matter does not produce a gravitational field strong enough to keep ahold of ordinary matter.
- Dark matter is not super dense (like a black hole around the centre of a galaxy). It is more "sprinkled" in a roughly-spherical halo throughout a galaxy. [9, 24] Its average density is still much greater than that of the normal matter in the galaxy because it's the dark matter that leads to the flat rotation curve of most galaxies. [42] If there were only baryonic matter, the rotation curve would drop off as $\propto 1/\sqrt{r}$ as Kepler's laws state. Whilst the surface density of dark matter does decrease with radius – so the density in a thin spherical shell around the galaxy decreases – its inclusive mass increases linearly (see Figure 1 in [22]) to compensate for the Keplerian drop off in the baryonic matter (think Gauss' law). [26, 36] The dark matter "orbits" the centre of the galaxy with the stars, but in some models has a lower velocity because it's angular momentum doesn't dissipate via collisions and collapse into a disc like baryonic matter does (because collisions would result in annihilation). In other models, it's corotational with the stars.

- Dark matter particles must be stable because they've existed for billions of years and have allowed galaxies to form in their potential wells.
- It is thought that dark matter was produced thermally in the early universe (when it was hot and therefore easier to create heavy particles). Dark matter particles could (and did) annihilate, but as the universe expanded and cooled the dark matter became more diffuse. They didn't annihilate as often and the dark matter we see today is a "thermal relic" and is what's left over. Some models suggest the parameter $x = m_{\mathrm{DM}}/T \sim 20$ at freeze out. [33]
- The current leading dark matter candidate is a WIMP (Weakly Interacting Massive Particle), possibly a neutral supersymmetric particle (neutralino) like a higgsino, photino, zino, etc. One of the motivations for WIMPs are that, using the current values of the dark matter density in the universe and approximations for the annihilation cross section, dark matter could self-interact at the electroweak scale to produce Standard Model particles. [31] As the EW scale can be readily accessed at colliders like the LHC, we could detect DM signatures via pair production then annihilation or indirect searches via solely annihilation.
- WIMP annihilation could produce two showers of quarks, which would normally be observed as pions and high energy photons (like gamma rays). The photons may be of a continuum – from hadronisation and radiation of the decay products of annihilation – or contain features (internal radiation from the propagator in the interaction or from loop-level processes).
- Because WIMPs are stable (at least on the timescale of the current age of the Universe), they wouldn't decay into other particles when produced from accelerator collisions. So you would detect them (indirectly) by looking for MET and by looking for visible particles recoiling against the WIMPs.
- The mediator (force-carrying particle, like the gauge bosons) for dark matter – between dark matter particles or the dark matter-Standard Model particle interactions – may be a scalar (spin-0, like the Higgs boson) or pseudoscalar (reverses parity under a Lorentz transformation, like the pion) boson. [Support] for a pseudoscalar over a scalar mediator comes from the Feynman diagrams for DM annihilation into, e.g., b-quarks. With a scalar mediator, the vertex factors and the propagator term lead to cancellations in the cross section equation in the low-velocity limit.
- The mediator for dark matter may be heavier than the dark matter particle itself (like with the $W^{\pm}$ and Z bosons being heavier than most of the particles they mediate),

maybe 2x heavier or more so than the DM particle. The mediator could decay via DM pair production, so it makes sense that it would be at least twice as heavy.

- There's no consensus on whether dark matter is fermionic or bosonic. If fermionic, it may be either a Dirac fermion (particle is distinct from its antiparticle, like the electron and positron) or Majorana fermion (particle is the same as its antiparticle, like the neutrino is suspected to be). If it were Majorana, dark matter could annihilate with itself, making discoveries via indirect searches more likely.
- At the LHC, monojets are used most prominently to look for dark matter particles. But multijet plus $E_{\mathrm{T}}^{\mathrm{miss}}$ might provide better sensitivity and constraints (particularly if the mediator is pseudoscalar).
- The Coma Cluster of galaxies seems to contain a very high concentration of dark matter (mass-to-light ratio of 400 solar masses per solar luminosity). See [50].
- Many dark matter candidates include a few supersymmetric particles (the neutralino being the most widely studied), sterile neutrinos [21], axions, Kaluza-Klein states [27] (which are excitations of Standard Model fields in extra dimensions), etc.
- Dark matter has to be cold (non-relativistic), as opposed to hot (relativistic), implying dark matter particles are reasonably heavy. If dark matter was light, it would have a lot of energy when produced in the early universe and would be relativistic (so hot). But if it were hot, it would be too diffusive to allow galaxies to form. However, because of the seemingly bottom-up nature of structure formation in the Universe [49] (smaller galaxies form first around clumps of dark matter, then orbit and merge with other galaxies to form clusters and larger elliptical galaxies), dark matter must be cold so it doesn't diffuse too much and can clump to allow galaxy formation.
- The different aspects of dark matter searches: indirect (annihilation), direct (scattering from SM particles), and collider (production). Try to find/make a good image that showcases this (Feynman diagram with arrows for each type of detection).
- Some good results showcasing dark matter masses and that of its mediator from different analyses and decay channels are at [1]. Particularly figures 4 and 6, which I used in my poster for the PGR conference.
- The 2015 results from Planck estimate the dark matter content of the universe to be 25.8%. It displays it in terms of $\Omega_c h^2 = 0.1186$, where $h = 0.678$ (the Hubble constant, in units of km s^{-1} Mpc$^{-1}/100$), giving $\Omega_c = 0.258$ as the cold dark matter density [44].
- Dark matter cannot be solely neutrinos because the flux densities of neutrinos (from

stars, as well as the cosmic neutrino background [48]) are precise and well-known, and due to the upper limit on neutrino masses [37], are too small to account for the dark matter content in the universe. Because the neutrinos have such a small mass, they would be highly relativistic in the early universe (as they are today, despite it being cooler now, making them slower) and so could only contribute to hot dark matter [45]. But as experiments show, the vast majority of dark matter must be cold.

- MOND (Modified Newtonian Dynamics) is one theory that tries to explain dark matter, and can be constrained to explain galactic rotation curves and other astrophysical phenomena attributed to it. However, any certain strand that tries to explain one observation usually falls flat when trying to explain others. It also doesn't work at all the scales to which we can observe the effects of General Relativity, almost confirming that GR is the correct description of gravity and MOND is a failure.

- LUX (Large Underground Xenon experiment) and LZ (LUX-Zeplin) are direct detection experiments that search explicitly for WIMP dark matter. LUX uses an underground liquid xenon tank to detect WIMPs interacting with ordinary matter, the scattering producing photons and electrons of specific energies. LZ is a collaboration between the LUX and ZEPLIN groups, and will have a highly-sensitive WIMP detector over a large range of masses, once completed.

- Evidence for non-luminous, *non-baryonic* matter (an argument for those who ask why dark matter can't be neutrons, etc.):

  One can use Doppler shifts of light emitted from galaxies in clusters, and therefore determine their masses. Then using the mass-to-light ratios of these galaxies and clusters (e.g., Bullet Cluster [12]), one can determine that most of the mass comes from non-luminous matter [19].

  One can also use the Cosmic Microwave Background to calculate the average photon and neutrino (mass/energy) densities and Big Bang Nucleosynthesis calculations to determine the baryonic matter density. These can be compared to other measurements (e.g, mass-to-light ratios averaged across the universe) and reveal the discrepancy [19].

  Neutrons can't contribute to dark matter because isolated neutrons are unstable, decaying in a matter of minutes [40]. They decay into protons and electrons. Being charged, they interact strongly with light and therefore contribute to the luminous matter in the universe.

Papers to look at regarding SUSY and dark matter:

[4]

[5]

[17]

[35]

[16]

[6]

[23]

[39]

[43]

[25]

[10]

[18]

[8]

- Discuss dark matter: motivation, evidence for its existence (and why it can't be neutrinos/dead stars/interstellar debris, etc.), detection methods and how we can probe it at the LHC (production). Should most of this stuff go in the introduction instead?
- Briefly outline particle accelerators and their function, the fact that we can use them to potentially discover dark matter or infer more of its properties, and the models that will be discussed in more detail to try and achieve this outcome.
- The introduction probably doesn't need to be too long, maybe only a few pages. Compare length with other people's theses (ask Ben Krikler for a copy of his, look at Alex's and Lana's).

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Doing the same to check both sides of the paper (for when it's bound).

Also testing glossaries: pileup, Large Hadron Collider, LHC, Large Hadron Collider (LHC).

Also testing references: [32] (article), [41] (book), [33] (inproceedings), [2] (techreport).

Testing numbers: 1234567890 (normal), 1234567890 (math), 1234567890 (from siunitx).

Testing alphabet: The quick brown fox jumps over the lazy dog

Testing math characters compared to normal text: b-tag, b-tag, b-tag, bbb$b\boldsymbol{b}$b, cccccc.

Testing equations: $^1/_2\rho\Delta\phi\mathcal{L}$ (inline)

$$B(P) = \frac{\mu_0}{4\pi}\int\frac{I\times\hat{r}}{\bar{r}^2}\mathrm{d}r \text{ (equation environment)} \tag{1.1}$$

Testing symbols/macros: eV, MeV, GeV, TeV, p_{T}, $p_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, $H_{\mathrm{T}}^{\mathrm{miss}}$, M_{T}, α_{dark}, r_{inv}, m_{χ}, $\mu\mu+\text{jets}$, $m_{\ell\ell}$, α_{T}, $t\bar{t}+\text{jets}$, $W(\rightarrow\ell\nu)+\text{jets}$, $\widetilde{\chi}_1^0$.

Chapter 2

Theory

This is the theory chapter.

- Give an overview of the fundamental forces and particles.
- Discuss the Standard Model in detail, emphasising certain aspects as they relate to dark matter and the Higgs field (and boson).
- Briefly recap dark matter, referencing descriptions in introduction.
- Discuss the theory behind combined Higgs to inv.: only SM process in which Higgs decays invisibly is $H \to ZZ \to 4\nu$ with branching ratio of 0.1 % [28], whilst the current observed experimental limit is 19 % from CMS [47] and 26 % from ATLAS [3]. If new, invisible particles couple to Higgs, branching ratio will be enhanced. Constraining $\mathcal{B}$ can also exclude some dark matter models.
- Discuss the theory behind the semi-visible jets analysis (main sources from Refs. [13, 14]): strongly interacting dark sector in Hidden Valley scenario with a portal to the visible sector. Mentioning dark quarks χ, dark confinement scale Λ_{dark}, dark hadronisation and decay, running coupling α_{dark}, etc.
- Explain some of the phenomenological/experimental event characteristics that overlap with both analyses, i.e., what a jet is, and maybe energy sums like $p_{\mathrm{T}}^{\text{miss}}$, H_{T}, $H_{\mathrm{T}}^{\text{miss}}$, etc.

2.1 The standard model of particle physics

2.2 Limitations of the standard model

2.3 Theoretical motivations for, and descriptions of, dark matter

2.3.1 Measuring the branching ratio for the invisible decays of the Higgs boson

2.3.2 Searches for semi-visible jets

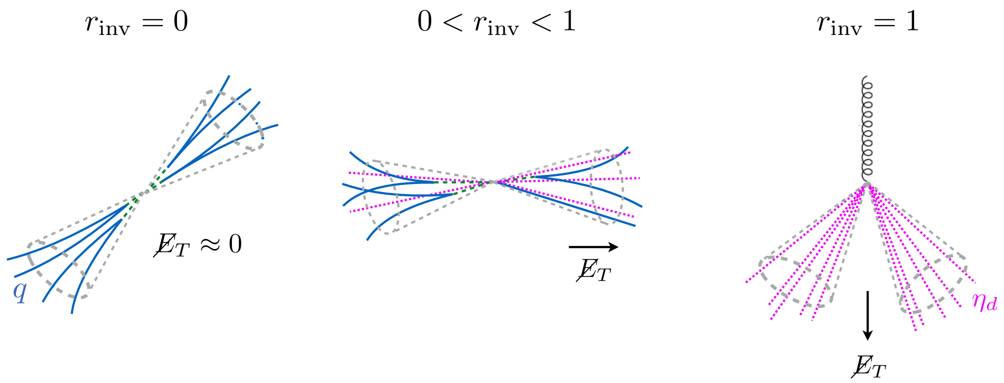


Figure 2.1: The typical direction of the missing transverse energy $\not{E}_{\mathrm{T}}$ (or $p_{\mathrm{T}}^{\mathrm{miss}}$) relative to the semi-visible jets as a function of their invisible fraction r_{inv} [14].

(a) s-channel (b) t-channel

Figure 2.2: Example Feynman diagrams for the two main production modes of semi-visible jets [14]. A Z' boson mediates the s-channel process while a bifundamental Φ mediates the t-channel process.

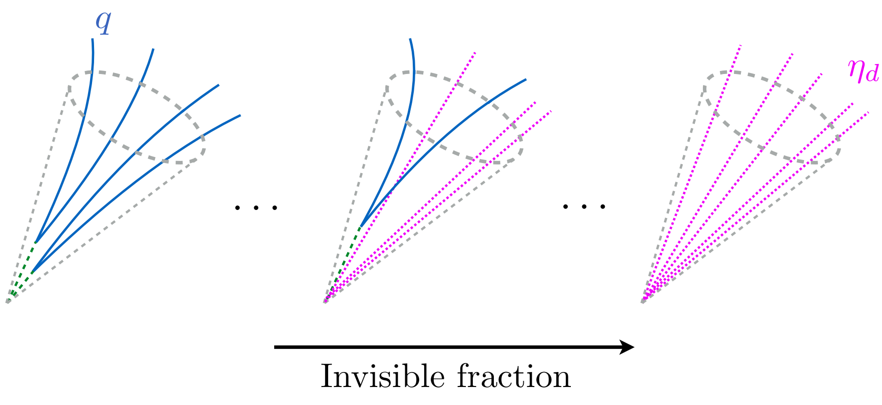


Figure 2.3: The constituents of a semi-visible jet as a function of its invisible fraction r_{inv} [14].

Chapter 3

The LHC and the CMS experiment

This is the detector chapter.

- Explain CERN and the LHC in more detail.
- Give an overview of the CMS experiment and detector (including all subsystems, object identification, algorithms for event/object reconstruction like Particle Flow and anti-k_{T} algorithm, and algorithms for tagging objects like b-jets).
- As a subsection in this chapter, discuss the Level-1 Trigger in depth. Emphasise the jet and energy sum triggers as I've worked on them, and Calorimeter Layer-2 for the same reason. Tie into SVJ and Hinv since they're hadronic searches.

3.1 The Large Hadron Collider

Deep underground beneath the Franco-Swiss border lies the Large Hadron Collider (LHC), a synchrotron particle accelerator 27 km in circumference. Predominantly a proton collider, lead and xenon ions have also been injected for novel and unique studies. Four principle experiments are situated at their own interaction points where the two beams of particles are brought into contact: CMS (Compact Muon Solenoid), a general purpose detector with interests in precision measurements, searches for new physics, and many other avenues; ATLAS (A Toroidal LHC ApparatuS), another general purpose detector with similar aims to CMS; LHCb, designed to study the decay of B hadrons; and ALICE (A Large Ion Collider Experiment), primarily studying heavy ion collisions and the quark-gluon plasma.

The LHC began operating in 2010 at a centre of mass energy of $\sqrt{s} = 7$ TeV (teraelectron volts), 3.5 TeV per beam. A modest increase to 8 TeV was achieved by the end of Run-1 in 2013. After upgrades were performed, the LHC resumed operation in 2015, further pushing the frontiers of high energy physics with a centre of mass energy of $\sqrt{s} = 13$ TeV. While valuable data was taken, it was not until 2016 when Run-2 of the LHC began. This period ended in 2018 with 162.85 fb^{-1} of pp collisions delivered, 150.26 fb^{-1} of which were recorded by CMS.

3.2 The CMS experiment

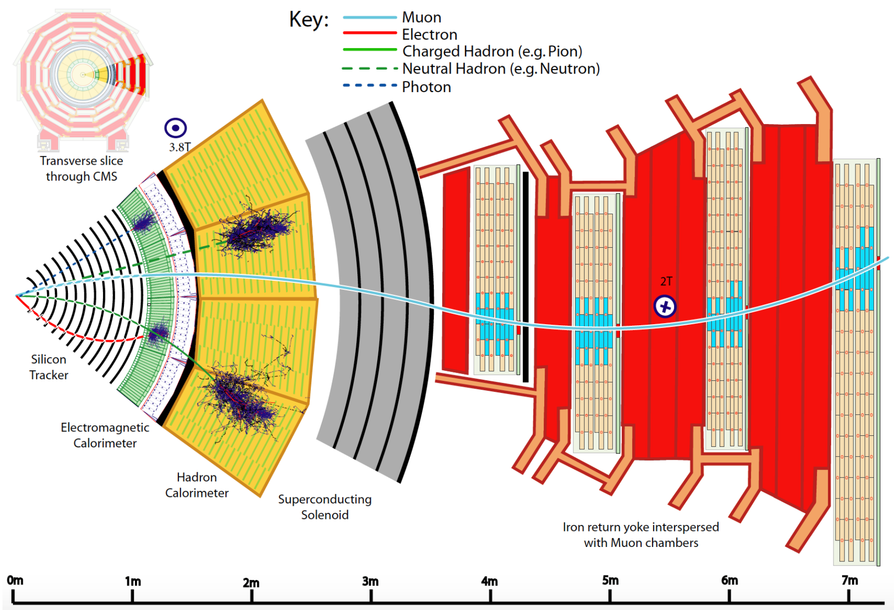


Figure 3.1: A transverse slice through the CMS detector with the main subsystems and components visible [46]. Several particles produced at the primary vertex and their interactions with the detector are also depicted.

3.2.1 Jet energy corrections in the Level-1 Trigger

Jet energy corrections (JEC) are necessary to compensate for various losses when recording jet properties in the trigger. These losses depend on the transverse momentum p_T and pseudorapidity η. The calibrations ensure that the performance of the trigger is uniform across the detector. Firstly, some ideal (or reference) jets are needed to compare against given L1 jets. Since Monte Carlo datasets are used for the calibrations, the reference jets we use are

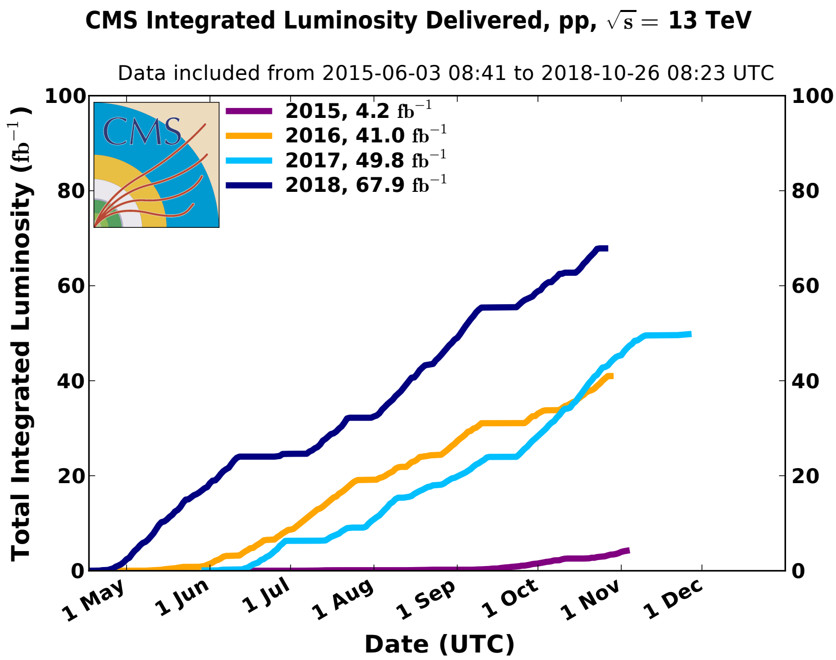


Figure 3.2: The integrated luminosity of pp collision data collected by CMS during 2015 and Run-2 of the LHC [15].

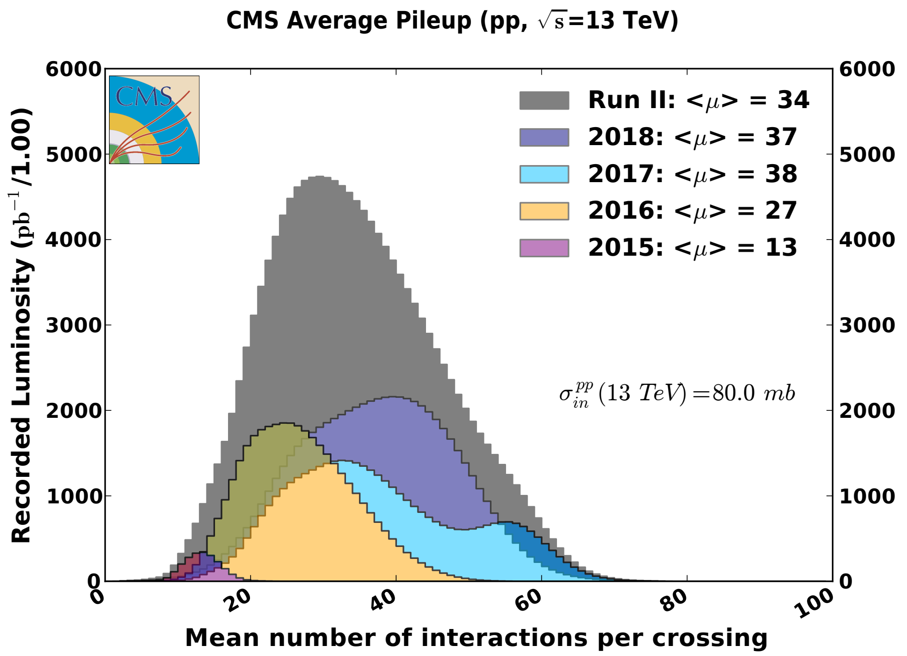


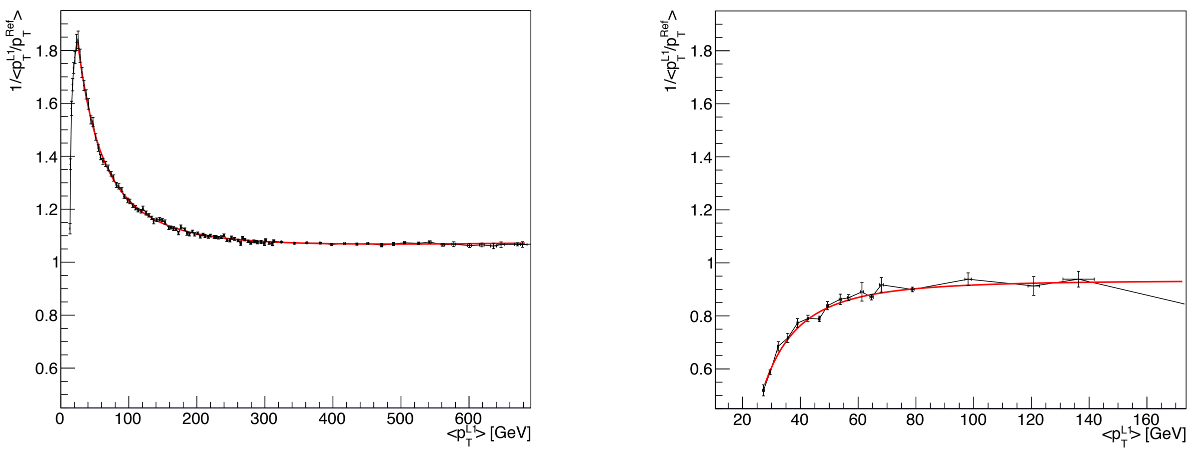
Figure 3.3: The average number of pileup interactions at CMS during 2015 and Run-2 of the LHC [15].

the generator-level jets (or GenJets). These are stable, simulated particles clustered with the anti-k_{T} algorithm algorithm [11] to form the jet. The state of these jets are post-hadronisation, before detector interaction. L1 jets need to be matched against the GenJets. From there, various studies can be performed such measuring the response ($< p_{\mathrm{T}}^{\mathrm{L1}}/p_{\mathrm{T}}^{\mathrm{ref.}} >$) of the detector, and its position and energy resolutions.

Once Calorimeter Layer-1 experts have derived scale factors for the physics objects, they are applied in Layer-2 where the calibrations are conducted. For jets, ntuples are created from the specified dataset and the L1 jets are matched to the GenJets using the variable ΔR:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \tag{3.1}$$

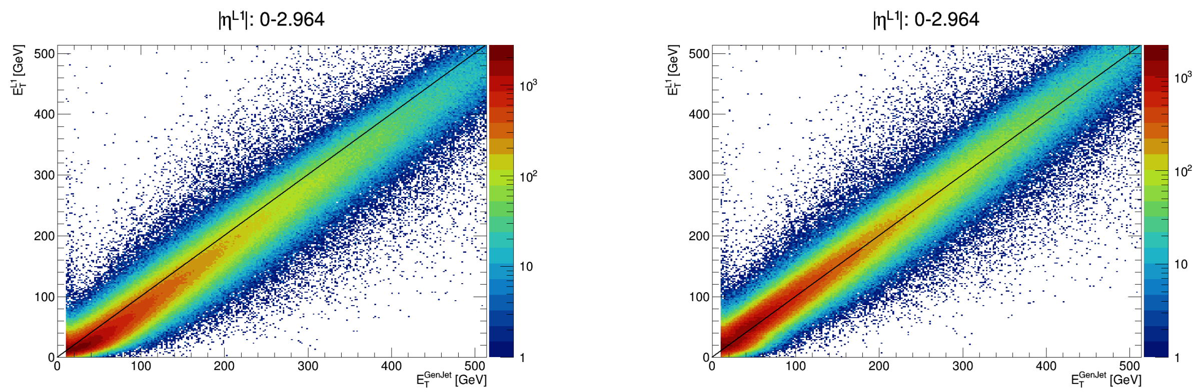
where ϕ is the azimuthal angle of the jet. The algorithm used to match the jets does so by inspecting each L1 jet in descending p_{T} and searching for a reference jet with $\Delta R < 0.25$. If there is more than one match, the reference jet with the smallest ΔR is taken. Then the next L1 jet (and so on) follows the same procedure, with the previous reference jet removed from the matching collection. Calibrations are then derived. The reciprocal of the response vs. $p_{\mathrm{T}}^{\mathrm{L1}}$ is plotted for each $|\eta|$ bin and correction curves are fitted to them (see Fig. 3.4). Once tuned such that the fit captures the low-p_{T} spike and high-p_{T} plateau, closure tests are conducted as the final step. The ntuples are remade with JECs and then matched with the reference jets to check that the calibrations have been properly applied. Plots such as Fig. 3.5 are then passed to the Trigger Studies Group to check over and continue the chain of trigger corrections and object calibrations.



(a) $0.435 < |\eta| < 0.783$ (Barrel)

(b) $4.191 < |\eta| < 5.191$ (HF)

Figure 3.4: Examples of correction curves used to calibrate the jet energies in two $|\eta|$ bins. The response is plotted against the p_{T} of the Level-1 jet and a complex function produces a fit. These plots are from the jet energy corrections performed on 2018 QCD Monte Carlo.



(a) Before corrections

(b) After corrections

Figure 3.5: The energies of matched pairs of jets in the entire barrel and end cap, before and after jet energy corrections have been applied. After calibrations, the distribution is much more symmetrical. An equivalent plot using jets from LHC data is expected to look similar after applying these calibrations.

Chapter 4

Combined search for the invisible decay of the Higgs boson in hadronic channels

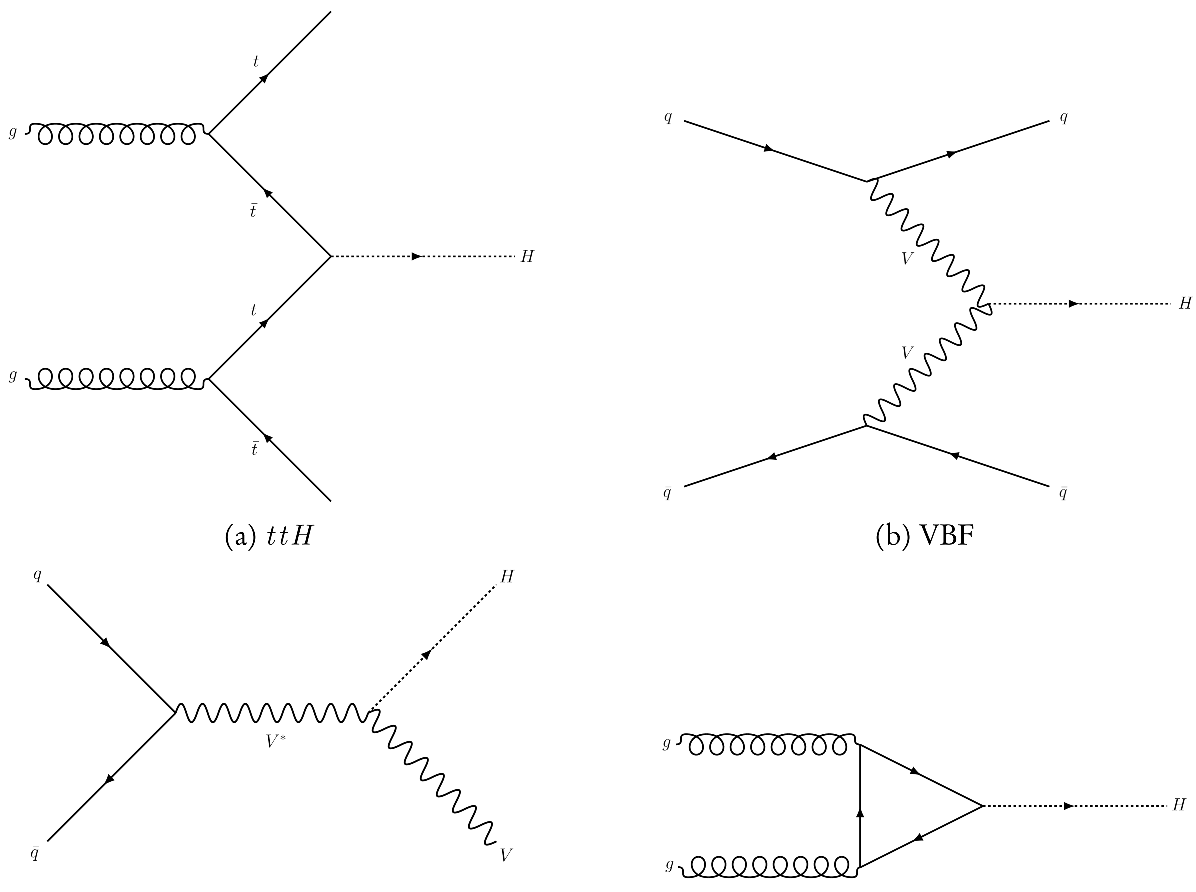
This is the analysis chapter on $H \to$ inv..

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.
- Discuss the necessity of including all production modes of Higgs (invisible final state, so characterise events based on initial/additional particles). Also mention how sensitive each production mode is at contributing to the branching ratio limit. Emphasise the non-VBF modes (ggF, ttH, VH – W^+H, W^-H, ZH) in this chapter as that's what I've been working on and another student will be covering VBF.
- Talk about what makes this analysis unique: doing a combination over all production modes from the start instead of separate analyses combined at the end. Means we can share samples, systematics, background methods and workflows, build in orthogonality between the different modes and cover as much phase space as possible (with new final states such as boosted Z bosons with unresolved subjets). This makes the analysis much more cohesive and consistent.
- Include object definitions, overall analysis strategy, triggers, signal production (with each non-VBF mode in detail), event selection, background estimation and results/limit (including comparisons to previous results).
- Emphasise my contributions: control region construction and studies, background estimation, and other studies I will have conducted by the time I write up.

– Current material: no public plots as of yet. Hope to finish analysis by the time I begin writing up. We are preparing a CMS internal analysis note, documenting all aspects of the analysis. I will add all relevant information there which I can subsequently use when writing this chapter.

4.1 Analysis overview

4.1.1 Hadronic production modes of the Higgs boson



(a) ttH (b) VBF (c) VH (d) ggF

Figure 4.1: The Feynman diagrams for the four main hadronic production modes of the Higgs boson.

4.2 Data and simulation

4.3 Triggers

4.4 Categorisation of the non-VBF production modes

4.5 Background estimation

4.5.1 Control regions

4.5.2 Background estimation methods

Chapter 5

Search for dark matter through the production of semi-visible jets

This is the analysis chapter on semi-visible jets.

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.

- Include object definitions, triggers, overall analysis strategy, signal production, event selection, background estimation and results/limit (including comparisons to similar searches – monojet/dijet exotic searches).

- Emphasise my contributions: s- and t-channel signal model production and understanding. Angular variable study for QCD background rejection (if used).

- Current material: no public plots as of yet. Hope to finish s-channel analysis soon (see previous section for caveats regarding inclusion), no timeline on t-channel analysis.

5.1 Analysis overview

5.2 Data and simulation

5.2.1 Generating signal samples in PYTHIA

5.2.2 Generating signal samples in MadGraph

5.2.3 Triggers

5.3 Background estimation

Chapter 6

Conclusions

This is the conclusion.

- Include a summary of thesis and work done over the course of my PhD with emphasis on the most important results/contributions.
- Mention the direction the semi-visible jet and Higgs to invisible analyses can take (sharing ideas/strategies I have, potential improvements with more LHC data and future prospects from potential future experiments).

APPENDIX A

APPENDIX A

Begins an appendix

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Glossary

***b*-jet** A jet identified by a given algorithm or classifier as originating from a b quark.

anti-k_T algorithm .

missing transverse energy The negative vector sum of the transverse momentum of all particles in a collider event. It is sometimes abbreviate to "MET", and also referred to in literature as "missing transverse momentum" (p_T^{miss}).

pileup The term ascribed to additional proton-proton collisions during a bunch crossing. Pileup interactions typically produce a large number of low-momentum particles.

semi-visible jet A shower of standard model and dark hadrons from the decay of a leptophobic Z' or Φ mediator that couples the hidden sector to the standard model.

Acronyms

ALICE A Large Ion Collider Experiment.

ATLAS A Toroidal LHC ApparatuS.

BSM beyond the standard model.

CERN Organisation Européenne pour la Recherche Nucléaire/European Organisation for Nuclear Research.

CMS Compact Muon Solenoid.

GeV gigaelectron volt.

JEC jet energy corrections.

LHC Large Hadron Collider.

LSP lightest supersymmetric particle.

QCD Quantum Chromodynamics.

SM standard model.

SUSY supersymmetry.

TeV teraelectron volt.

VBF vector boson fusion.